Earth's Radiation Belts: A Tutorial

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Special thanks to: S. Kanekal, , I. Mann, X. Li, S. Elkington, M. Wiltberger



LWS Geospace

Atmospheric Coupling





Outline of Talk

I. Introduction

II. Key Observational Results

- Coronal Mass Ejections
- High-Speed Solar Wind Streams

III. Radiation Belt Particle Acceleration

- Local Heating Processes
- Radial Diffusion
- Numerical Simulations
- IV. Electron Losses and Atmospheric Coupling
 - Loss Processes
 - Atmospheric Chemistry Effects
- V. Future Programs and Summary





Earth's Radiation Belts





Some Frequently Used Platforms

SAMPEX

-LEO orbit $\approx 600 \text{ km}$ POLAR -Elliptical 2x9 R_E Orbit GEO

-Geostationary Earth Orbit – $6.6 R_E$

Magnetospheric Regions and Currents



Key Observational Results



Solar Cycle View of Solar Wind Effects





Coronal Mass Ejection - Earth Impact







Relativistic Electrons & Geomagnetic Storms



- Recovery phase
 - Increased fluxes
 - Energization
- Main phase
 - Flux dropout
 - Adiabatic field change & particle loss
- Flux changes
 - Decrease or no change in about 50% of storms
 GEO data



SOHO Images of the Sun: Halloween 2003







IMAGE EUV Plasmasphere Data



Data courtesy J. Goldstein

Baker et al. (Nature, 2004)



Coldest Plasmas Control Hottest Particles!

- a. Normal plasmasphere/radiation belt location under typical conditions
- b. Distorted plasmasphere/radiation belt during October/November 2003 storm





Baker et al., [Nature, 2004]









(Yohkoh soft X-ray images)







Relativistic Electrons: Energization



- High solar wind speeds

 (> 500 km/s) and
 southward B_z
- Substorm-generated seed population (extending to hundreds of keV)
- Physical processes
 - radial transport
 - in-situ acceleration

Anik Failures: Deep-Dielectric Charging



remarkable times for V_{SW}

Some Key Questions About "Killer" Electrons Are they really killers?

... or just misunderstood?

Did they start out bad?

... or did they have an unfortunate home life?

If they are killers?

... was it self-defense?

Will the Boulder police and crack NOAA security forces combine...

...to solve the mystery of the killer electrons?



Electron Acceleration



Adiabatic Invariants

Associated with each motion is a corresponding *adiabatic invariant:*

- •Gyro: $M = p^2/2m_0 B$
- •Bounce: K
- •Drift: L









- M: perpendicular motion
- K: parallel motion
- L: radial distance of equator crossing in a dipole field

If the fields guiding the particle change slowly compared to the characteristic motion, the corresponding invariant is conserved.

Inner Magnetospheric Particle Properties

The inner magnetospheric particle population may be completely characterized at a point in time by its *distribution function*:

$$f = f(x, y, z, p_x, p_y, p_z)$$

Also referred to as the *phase space density*, *f* gives the number of particles in a volume (x+dx, y+dy, z+dz), with momenta between (p_x+dp_x , p_y+dp_y , p_z+dp_z).

The flux in a region of space may be related to the distribution function through

$$f = \frac{j}{p^2}$$







Acceleration by Radial Transport

Nonrelativistically, and in a dipole,

$$M = \frac{p^2}{2m_0 B} = \frac{WL^3}{B_0}$$

or

$$W = \frac{MB_0}{L^3}$$

so transport in *L* while conserving *M* will necessarily lead to change in energy, *W*.





Boundary Conditions: The Plasma Sheet as an Outer Boundary Source?

- keV electrons in the plasmasheet convect inward: W increases → more grad-B drift
- Alfven layer marks boundary between open and closed trajectories; *r*₀ increases with *M*, decreases with convection *E*
- r₀ for MeV geosynch electron beyond magnetopause
- Wish to investigate whether and when plasmasheet electrons may act as a source of MeV radiation belt particles





N. Tsyganenko

http://nssdc.gsfc.nasa.gov/space/model/magnet os/data-based/modeling.html

Elkington et al. (JASTP, 2004)

MHD Simulation of a Strong Storm



MHD/Particle Simulations of Energetic Electron Trapping

- 60 keV test electrons, constant M
- Started 20 R_E downtail, 15s intervals
- Evolves naturally under MHD *E* and *B* fields
- Removed from simulation at magnetopause
- Color coded by energy





Electron Losses



Dynamic Radiation Belts: 1993-1995



Radiation Belt Mapping 2-6 MeV electrons in the magnetosphere











Sources of Atmospheric Ionization

Atmospheric Particle Coupling



Future Programs and Summary



The Radiation Belt Storm Probes (RBSP) program



Radiation Belt Storm Probes (RBSP) constellation

Science Objectives:

- 1. Differentiate among competing processes affecting the acceleration and loss of radiation belt electrons;
- 2. Understand the creation and decay of new radiation belts;
- 3. Quantify the relative contribution of adiabatic and nonadiabatic processes;
- 4. Understand the role of "seed" or source populations; and
- 5. Develop and validate specification models of the radiation belts.

RBSP addresses the scientific and programmatic goals of the NASA Living With a Star program.

LASP

International Living With a Star Program (RBSP and ORBITALS)





Summary

- We have a long and intriguing record of Earth radiation belt observations
- Rapid, powerful particle acceleration can occur on short time scales within the radiation belts
- Both local heating and radial transport are important
- Powerful losses can lead to coupling with the deeper atmosphere
- New missions that are underway should lead to remarkably good science closure in the near future, more than 50 years after James Van Allen's pioneering discoveries



Thank you—Questions?



Top Ten Reasons to Worry About Radiation Belt Changes

- 10. Communication satellite disruptions prevent C-Span from showing Congress at work. (No one notices).
- 9. Large solar wind stream event and electron enhancement causes New York cab drivers to speak perfect English.
- 8. High particle radiation on space shuttle makes Coca-Cola taste just like Pepsi.
- 7. Magnetic storm sends crazed homing pigeons on a pecking rampage.
- 6. Pipeline corrosion interrupts flow of Cheney/Bush retirement funds from Iraq.
- 5. Solar particles in outer belt cause Barack Obama to lose all judgment: Stars in really bad TV movie called "Solar Flare 2009".
- 4. Hubble Space Telescope has upset in South Atlantic Anomaly and can only be pointed at Osama bin Laden's cave.
- 3. Increased atmospheric-energetic electron coupling causes Air Force One to make emergency aircraft carrier landing.
- 2. Radiation belt enhancement causes Katie Couric to do CBS Evening News in thick Italian accent.

And the Number 1 reason to worry about rad belt changes:

1. Astronauts go berserk in zero-gravity pie eating contest!

